Coupled Optoelectronic Oscillators: Application to Low-Jitter Pulse Generation

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Actively mode-locked Erbium-doped fiber lasers (EDFL) have been studied for generating stable ultra-fast pulses (< 2 ps) at high repetition rates (> 5 GHz) [1,2]. These devices can be compact and environmentally stable, quite suitable for fiber-based high-data-rate communications and optical ultra-fast analog-to-digital conversions (ADC) [3]. The pulse-to-pulse jitter of an EDFL-based pulse generator will be ultimately limited by the phase noise of the mode-locking microwave drive (typically electronic synthesizers). On the other hand, opto-electronic oscillators (OEO) using fibers have been demonstrated to generate ultra-low phase noise microwaves at 10 GHz and beyond [4]. The overall phase noise of an OEO can be much lower than commercially available synthesizers at the offset-frequency ranges > 100 Hz. Clearly, ultra-low jitter pulses can be generated by taking the advantage of the low-phase noise of the OEOs. In this paper, we report the development of an integrated approach by combing the two technologies. In this approach, the optical oscillator (mode-locked EDFL) and the microwave oscillator (OEO) are coupled through a common Mach-Zehnder (MZ) modulator, thus named coupled opto-electronic oscillator (COEO). Based on the results of previous OEO study, we can expect a10 GHz pulse train with jitters much less than 10 fs.

Opto-electronic oscillator is a new type of microwave oscillator that converts light wave energy into stable and spectrally pure microwave. As shown in Figure 1, an microwave signal is modulated onto the optical carrier, recovered by the photo-receiver after through a long fiber delay line, and fed back to the modulator with the proper phase and gain to compete the oscillator loop. Because of the low transmission loss of optical carrier through a long piece of fiber, the equivalent resonator Q resulting from the long delay is high, which makes low phase noise possible. It can be shown that the spectral density of the phase noise at a given offset frequency is inversely proportional to τ^2, where τ is the delay time through the fiber [4]. For example, with a 6 km fiber, the phase noise of 140 dBc at 10 kHz can be readily obtain at 10 GHz and higher, which is at least 40 dB lower than any commercial synthesizer. With more sophisticated carrier suppression scheme, additional 20 dB or more can be suppressed [5].

The simplest mode-locked EDFL consists of a fiber ring loop with an erbium-doped fiber amplifier (EDFA) as the gain medium and a MZ modulator as the mode-locker, also shown in figure 1. When a microwave signal is applied to the mode-locker with the frequency equal to an integer number of the free spectral range of the laser cavity, it strongly modulates the intra-cavity optical signal and therefore couples all the relevant intra-cavity modes. With typical EDFL parameters, however, this usually can only produce pulses 5 ps or wider according to Kuizenga-Siegman's limit [6]. Shorter pulses

(< 2ps) can be obtained through self-phase modulation (SPM) and intra-cavity dispersion compensation [1]. In our mode-locked EDFL setup, a 100 m dispersion compensation fiber was used to not only reduce the average loop dispersion to 1.4 ps/nm/km but also provide long enough fiber for sufficient SPM. The EDFA had a saturated output power of 50 mW. With the microwave frequency at 7 GHz and no optical filter used, we obtained near transform-limited 2 ps pulses with the time-bandwidth product of 0.34. However, the pulse-to-pulse jitter was higher than the phase noise of our synthesizer. The main instability comes from the fiber polarization fluctuation in the optical loop. Adapting the Sigma laser configuration [7] in the near future will eliminate this fluctuation.

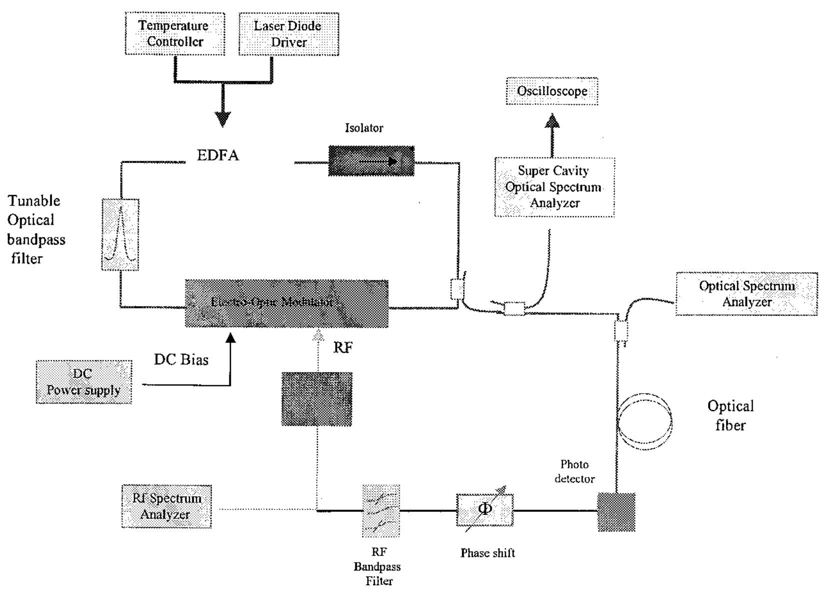

Figure 1 Schematics of COEO with the mode-locked EDFL in a ring configuration. Dashed frames show separately a) the mode-locked laser and b) the OEO.

The proposed COEO approach replaces the external laser source in an OEO with an EDFA-based ring laser as shown in figure 1. The modulator in the OEO is also the mode-locker in the EDFL. The OEO derives the microwave signal from the beat note of the mode-locked laser, properly filtered and amplified and phase-shifted, and fed back to drive the mode-locker. In our COEO setup, the ring laser configuration was again used. A 1 nm bandpass filter was inserted in the optical loop. The microwave bandpass filter selects a specific microwave mode to oscillate. At 7 GHz, a Q of 120 is adequate to make the OEO run single mode with nearest modes more than 40 dB below the carrier. Interestingly, we have been able to demonstrate that the COEO can oscillate without any microwave amplifier in the OEO loop. This is because of the strong mode-locking tendency near resonance. Under favorable conditions, in fact, only less than −10 dBm rf power is needed at the modulator to generate over 5 dBm rf power at the detector. In any case, with the present COEO, the phase noise of the microwave signal from the COEO was not as low as a typical OEO. Again, the polarization fluctuation in the EDFL loop is the main cause. It should be pointed out that the supermodes will have to be strongly suppressed to achieve the lowest jitter possible. The supermodes are other equivalently possible modes in the mode-locked laser due to the fact it is mode-locked at very high harmonics of the fundamental mode (on the order of 10,000). The supermodes are largely suppressed through the strong mode competition. The effect of self-intensity stabilizing through the balance of SPM and bandwidth limitation helps greatly in reducing amplitudes of the supermodes [8]. We also plan to use an intra-cavity etalon in the optical loop to further suppress the supermodes for achieving the lowest jitter possible.

In conclusion, we have demonstrated an EDFL-based coupled opto-electronic oscillator as well as the generation of the transform-limited 2 ps pulse trains at 7 GHz. By eliminating the polarization fluctuation in the optical loop and further suppressing the supermodes, we should be able to generate ultra-low jitter ultra-fast pulses in a single all-photonic package.

References:

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